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ABSTRACT
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Momentum control of liquid-fuelled service vehicles

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MOMENTUM CONTROL OF LIQUID-FUELLED SERVICE VEHICLES

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High-performance service vehicles require liquid fuel. The essential idea for achieving fail-safe operations is to have a spacecraft that starts to rotate under thrust. Then, if control would fail, thruster action will produce spin that keeps linear momentum small. The paper addresses possible performances only, not acceptably safe implementation. A partially filled tank allows liquid mass excursions, including swirl and increasing liquid angular momentum. The equations for a simplified case in two dimensions are presented. The liquid fuel is modelled as a point mass that is constrained to remain on an ellipse about a reference point (the tank centre on the spacecraft). The dynamic behaviour of the compound system is illustrated for 3-D and spin-stabilised nominal states. Two problems are considered, the build-up of maximum linear momentum and the reduction to zero of the angular momentum of the spacecraft. Different tank dimensions, leading to different inertial parameters, are chosen to get examples with certain stability properties. Simulation of the spin-stabilised case requires use of the Sloshsat Motion Simulator SMS, with nonzero liquid mass dimension. Sloshsat FLEVO is a small experimental spacecraft that is prepared for launch from the STS, to investigate liquid dynamics in space. Control of Sloshsat is effected by a law as analysed with the simple 2-D model in this paper.

1. Introduction

Manoeuvring service vehicles are to perform various functions, and some may occur near the International Space Station ISS. Operation of these spacecraft constitutes a hazard, as such vehicles are capable of linear momentum build-up and collision with ISS or other close bodies. A component of the strategy to achieve safety, is propulsion by a cold-gas system of minimal capacity. The maximum amount of linear momentum that can be generated in any circumstance will then remain small. The drawbacks are limited operational capability, frequent refuelling and (orbital) stored gas maintenance. The fail-safe operation of service vehicles with liquid fuel propulsion must deal with the large potential for linear momentum. Obvious docking hazards could be avoided via special tank designs - e.g. such that inhibit liquid slosh by contracting to zero the ullage space in the tank. A better solution is to develop a validated model for liquid behaviour in a partially filled tank. The system has additional degrees of freedom as compared to an invariable body. A good model opens the option to exploit the variation in the location of the liquid centre of mass (c.o.m.) for fail-safe operations. It is this option that will be explored in the paper. The idea is to inhibit inadvertent build-up of linear momentum by spacecraft (tank) design such that active control is required for stable translation.

A spacecraft can be unstable under thrust, but one could also create instability by deliberate control actions. Safe operation then requires successful adjustment of the parameters that make the control stabilising. Unstable/unplanned operation is to result in fuel to be spent on angular, rather than linear, momentum generation. This may then be countered via reaction wheel control and removed later. The analysed motions are simple but are basic to most manoeuvres. The specific docking hazards are not addressed, these involve highly constrained operations only and concern much wider classes of spacecraft.

Active control is effected via implementation of flight software. Consequently, it is required to have software development standards that yield acceptable safety. A similar situation exists in many fields, for example in process engineering, or in civil aviation where take-off and landing and other critical actions require certified system operations software. These important issues will not be discussed any further here, see Reference 1.

The impetus for the paper arose from the discussions with NASA safety staff in connection with the planned operations of the Sloshsat FLEVO spacecraft[2] (mass is 129 kg, including 33 kg water in a 87 liter tank). This experimental vehicle, for the investigation of liquid dynamic effects onboard satellites, is to be operated in the vicinity of the Space Shuttle (STS). A recontact hazard was identified, meaning that Sloshsat might reach STS within 10 hours if control software were to fail selectively. At that occasion it became apparent also that no safe software development standard has been adopted for such operations yet.
The principal tool for the investigation is a 2-D model[3] of a rigid spacecraft with a point mass that is constrained to move on a (near) elliptical trajectory.

2. Nomenclature

Figure 1 legend:

m = liquid point mass
M = tank mass
I_{yy} = tank principal moment of inertia (m.o.i.)
a = tank c.o.m. co-ordinate along major axis
b = tank c.o.m. co-ordinate along minor axis
d = thrust direction offset from major axis
$l = L + \gamma \cos \varphi$ = distance of m to tank center
γ = difference between the extreme and the average radius of the trajectory of m; < L/5
φ = angular co-ordinate of m in the tank
ψ = normal direction to the trajectory of m
θ = tank rotation from an inertial reference
N = normal force between m and tank
S = force on m with magnitude $sf^*\varphi' + sp^*\sin2\varphi$
F = thrust force on tank
T = torque from **S** and control $\mathbf{T}_c$

The non-bold capital gives the size of the force vector e.g. $T = T_c + S\ (l + a\cos\varphi + b\sin\varphi)$

Other:

$'$ = time derivative
τ_d = control delay period
K = control gain
g = F/M
$\mu = m\,M/(m+M)$
$\delta = l\sin(\psi-\varphi) + a\sin\psi - b\cos\psi$
$J_y = I_{yy} + \mu b^2$
Bo = m g /sp for a tank fill ratio near 0.5

3. Vehicle model

In order to assess options for control, a 2-D spacecraft model has been defined. It is based on two interacting masses; the architecture is sketched in Figure 1. The annotations have been explained in the Nomenclature above. The model has some similarity with a rigid spacecraft with an elastic beam since the system center of mass (c.o.m.) varies with respect to the rigid part, and resonance frequencies are generated by capillary potential. Additionally, liquid swirl around a closed trajectory is a cause of periodic interaction force. The ratio between weight and capillary forces is m g/sp , and is commonly denoted by 'Bond number'. The dynamic equations are integrated in a Matlab program "allips2" . In the next section some simulation results will be discussed to exhibit typical dynamics that may possibly be exploited in system studies. Throughout, parameters and variables have been given values in kg-m-s system units.
A similar model, but apparently without capillary effects (sp = 0) , has been used to prepare the control of the STARDUST spacecraft[4] , and for investigations of its stability.

The model has dependent variables θ and φ which leads to a state vector with four components: $\theta' = \theta_1$, $\varphi' = \varphi_1$, $\theta_1' = \theta''$ and $\varphi_1' = \varphi''$.

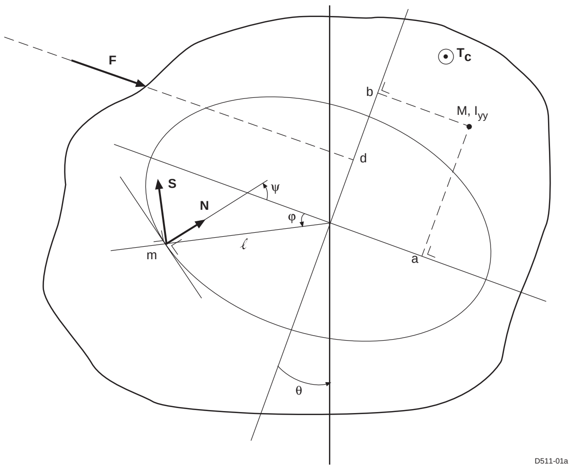

Figure 1 Architecture of the 2-D spacecraft model in allips2.

The system of differential equations that describe the model, consists of the two equations that define θ_1 and φ_1 , and equations (1) :

$$\begin{bmatrix} I_{yy}\cos(\psi-\varphi)/\mu+\delta(a\sin\varphi-b\cos\varphi) & -2\delta\gamma\sin2\varphi \\ I_{yy}\sin(\psi-\varphi)/\mu+\delta(l+a\cos\varphi+b\sin\varphi) & \delta l \end{bmatrix}\begin{bmatrix}\theta_1' \\ \varphi_1'\end{bmatrix} =$$

$$\begin{bmatrix} \delta\{l(\theta_1+\varphi_1)^2+4\gamma\varphi_1^2\cos2\varphi+(a\cos\varphi+b\sin\varphi)\theta_1^2\}+ +g\{M(b-d)\cos(\psi-\varphi)/\mu+\delta\cos\varphi\}+T\cos(\psi-\varphi)/\mu \\ \delta\{4\gamma\varphi_1(\theta_1+\varphi_1)\sin2\varphi-(a\sin\varphi-b\cos\varphi)\theta_1^2\}+ +g\{M(b-d)\sin(\psi-\varphi)/\mu-\delta\sin\varphi\}+\{T\sin(\psi-\varphi)-\delta S\}/\mu \end{bmatrix} \quad (1)$$

4. Model stability

The state equations (1) are non-linear and therefore need to be linearized about an operating point φ_{ref} , or the classical stability theories will not apply.
In absence of motion (1) yields two equations that contain T_c and S. Elimination of S results in a single expression for T_c as a function of the location of the liquid mass m. To investigate the hydrostatic stability put $\gamma = 0$, a convenient simplification which makes $\varphi = \psi$ and $l = L$. Neglect products of θ' and φ' and get from (1):

$$(I_{yy} + \mu\delta^2)\,\theta'' = g\{M(b-d) + \mu\delta\cos\varphi\} + T \qquad (2)$$

$$(L + a\cos\varphi + b\sin\varphi)\theta'' + L\varphi'' = -g\sin\varphi - S/\mu \qquad (3)$$

For small motion the control torque must be close to:

$$T_{c\,ref} = F\,[\,M(d-b) + m(d + L\sin\varphi_{ref})]\,/\,(m+M)$$

Redefine T_c as the deviation from $T_{c\,ref}$ and φ as the deviation from φ_{ref}, then for motion near $\varphi_{ref} = 0$:

$$J_yL\varphi'' + sf*\mu^{-1}\{\mu(a+L)^2 + J_y\}]\varphi' + [g\{\mu a(a+L) + J_y\} +$$

$$+2sp*\mu^{-1}\{\mu(a+L)^2 + J_y\}\,]\varphi + (a+L)\,T_c = 0 \qquad (4)$$

obtained by substitution of (2) in (3) .

If in (4) the sign of the coefficient of φ is reversed, and '–a' is substituted for 'a' , the equation describes the motion near $\varphi_{ref} = \pi$.

Replace in (2) and (3) the derivative $'$ exponent by a coefficient s, such that e.g. $\varphi'' = s^2\ \varphi$, and derive $T_c = p(s)\theta$ where p(s) is a quotient of polynomials in s. If $T_c = -K\,\theta'(t-\tau_d)$, or in s: $T_c = -K\,s\,\theta\,\exp(-\tau_d\,s) = p(s)\theta$, then divide out θ and a function in s results. For small $\tau_d\,s$: $\exp(-\tau_d\,s) \sim (2-\tau_d\,s)/(2+\tau_d\,s) \sim -p(s)/(K\,s)$ yields a quartic in s of which the roots determine the stability of system(2) and (3) , following standard control theory. If $T_c = 0$, the stability of the liquid location is given by the sign of the coefficient of φ in (4):

$$g\{\mu a(a+L) + J_y\} + 2sp*\mu^{-1}\{\mu(a+L)^2 + J_y\} = \qquad (5)$$

$$sp*m^{-1}[Bo*\{\mu a(a+L) + J_y\} + 2(1+m/M)\{\mu(a+L)^2 + J_y\}]$$

Of the parameters in this coefficient, μ, J_y and L have positive values. A negative value of sp means that the capillary force tries to settle the liquid at the locations $\varphi = \pm\,\pi/2$. When liquid mass m gets consumed, μ is reduced in value. The consequent variations in magnitude of sf and sp will require more information on tank geometry and fill ratio. For large Bond number the capillary effects are seen to be negligible. Although the modeling that leads to (4) has used phenomenological data, the equation as such stands to be validated by experiment.

The instability as predicted by (5) is explored. A critical m.o.i. is defined : $I_{yy\,crit} = -\mu a(a+L)$, requiring $0 > a > -L$. With parameter values for the Sloshsat spacecraft $I_{yy\,crit}$ gets a very small, irrelevant value. For a realistic m.o.i. it is necessary to assume, say, L = 1.2 m and a = –0.6 m, appropriate for a tank cavity shaped like a giant bicycle tire (or a nutation damper).
In the sequel the spacecraft with these data will be referred to as Tiresat. With the assumptions b = d = 0, sf = sp = 0, F = 1.57 N (the Sloshsat value) and with I_{yy} reset to 10 % larger or smaller than the $I_{yy\,crit}$ value, Tiresat has been implemented in the Matlab code for (1). Simulations have been run for 1000" from zero initial conditions, except for $\varphi_0 = 0.02\,\pi$. The predicted inertial velocity components of the tank are presented in Figure 2.

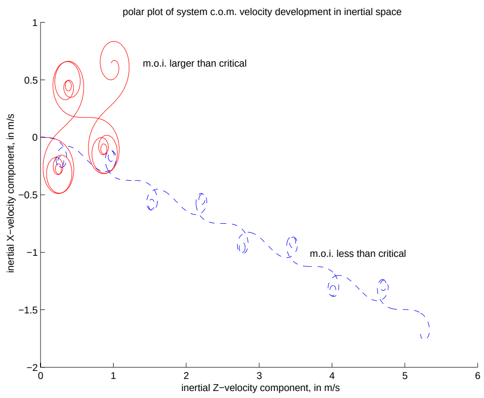

Figure 2 Simulation of inertial velocity components of a sub- and a super-critical Tiresat

The subcritical case is unstable, as predicted by (5), and shows 'curls' in the velocity plot. These correspond to large values of θ, and alternatively positive and negative values of θ', see Figure 3. The instability is found to consist of a rapid swirl of the liquid about the tank, to settle again in its initial state. Each 'curl' causes fuel to be spent without net linear momentum growth.

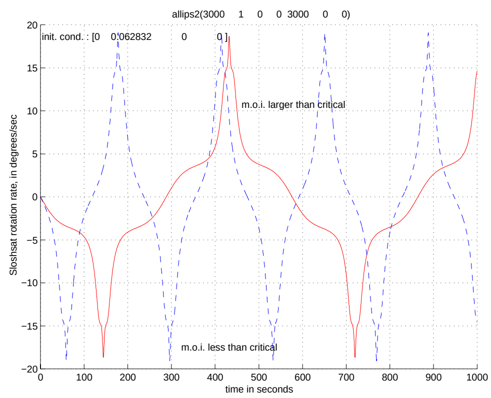

Figure 3 Tank rotation rate corresponding to the motion in Figure 2.

The supercritical case, stable according to (5), was found unstable for the chosen value of φ_0 . When the value is decreased to 0.01π , stability is achieved and the velocity plot becomes parallel to the subcritical. However, the 'curls' are absent and the plot extends farther since more linear momentum is generated. The tank rotation plot, Figure 3, similarly is without the peaks from liquid swirl. The small momentum build-up for the unstable supercritical case, as shown in

Figure 2, apparently is related to the long period between the successive liquid swirls.

When d = 0.05 m, which offsets the thrust from the tank geometric center and tank c.o.m. , a nonzero $T_{c\ ref}$ is introduced. If its value cannot be generated exactly by the Reaction Control System (RCS), the systematic difference T_c gives the tank a rotation rate that inhibits the generation of large linear momentum values. The simulations show as much. Thence, momentum build-up for (nonspinning) spacecraft with liquid is unlikely, for the same reason as it is for rigid spacecraft in absence of attitude control, viz. systematic torque from misalignment of thrust. Nevertheless, it is difficult to predict just how much magnitude can be attained. In unplanned uncontrolled conditions with active thrusters, the achievable magnitude may easily be too large for safe operations.

The option that presents itself from (5) is to design the tank for desirable stability of liquid mass position φ . Thrust is generated only if the fuel is positioned at the exit of the tank, and so could be cut if the fuel moves as a consequence of an abnormal state of the system. To exploit this option successfully, one needs to take into consideration also the performance of a Propellant Management Device (PMD) that normally is included in a tank for a 3-D stabilized spacecraft.

5. Spin stabilisation

Various tasks for a service vehicle may require a basic spin rate. If the spin is about the maximum m.o.i. , the system is unconditionally stable and propulsion along a direction parallel to the spin vector might increase linear momentum without need for control torque. Propulsion will displace the liquid c.o.m. and thus change the system inertia tensor. In order to illustrate what happens in this case, simulations have been run with the Sloshsat Motion Simulator, or SMS[5] for spacecraft data of Sloshsat. The thrust vector along the axis of maximum dry m.o.i. does pass within a few centimeters of the dry c.o.m. The liquid mass is centrifuged out to one end of the tank and stably held by capillary equilibrium. Initially, the system c.o.m. also is displaced some centimeters from the line of thrust. Figure 4 shows the predicted build-up of linear momentum during 200 " of thrust, for the low initial rotation rate of $0.2\ s^{-1}$ and no control. Note that hardly any momentum is generated in one inertial direction normal to the stable direction.
Other simulations with higher initial rates gave similar predictions. The momentum build-up normal to the stable direction decreases with higher initial spin rate.
The liquid mass moves about in the tank, with large excursions, but an average location can be observed.

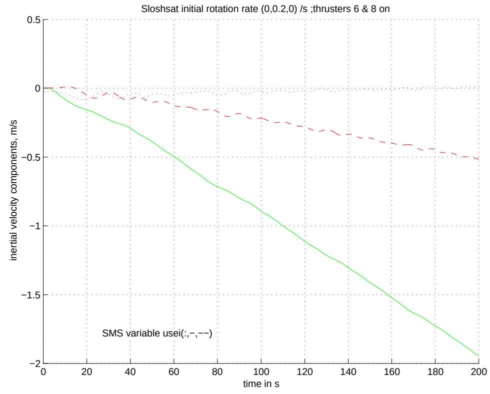

Figure 4 Sloshsat linear momentum build-up during stable spin

The thrust results also in an increase of angular momentum; the predictions are plotted in Figure 5. If the initial spin rate is higher, the components normal to the stable direction do not grow as large.

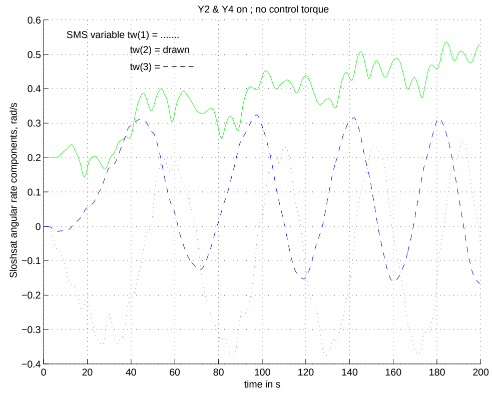

Figure 5 Angular rate development during the motion in Figure 4.

6. Controlled motion

For the elaboration of control issues, the RCS of Sloshsat will be taken as representative. It includes 12 thruster nozzles arranged about the spacecraft for the generation of force and torque. The thrusters form six tandem pairs, two opposing tandems for each Cartesian direction. A pure torque is generated by firing two thrusters offset in opposing tandems. The control law determines the required (vector) values that are to be realized during the RCS activation period. For closed loop control there will be some (periods) delay τ_d between the current knowledge about the state, and the consequent reactions. Magnitudes are realized by time modulation: an activation period consists of a (fixed) number of thruster pulse periods (33 ms for Sloshsat) each of which may have the thruster 'on' or 'off'. A special algorithm translates the force and torque requirements to 12 sequences of thruster on/off commands, one sequence for each thruster. Other control scenarios exist, e.g. direct commanding of thruster activation, but those will not be considered .

Sloshsat has no instruments for attitude determination and will use rate control to execute its manoeuvres.

The quartic stability polynomial of its 2-D model has roots with negative real parts for the considered cases. Consequently, the system is stable.
Simulations for the case $T_{c\ ref} = 0$ rather than the true value, with the rotation rate controlled to zero and with continuous thrust, show a curved spacecraft trajectory and a consequently finite maximum speed for any duration of thrust. This occurs because the thrust vector is offset from the system c.o.m. and a nonzero $T_{c\ ref}$ is generated by the control system. Since the control torque is prescribed proportional to the angular rate, a (deterministic) rotation rate results. If the correct value of $T_{c\ ref}$ is prescribed to the RCS, the rate is negligible as exemplified in Figure 6 by the curve annotated with Tiresat.

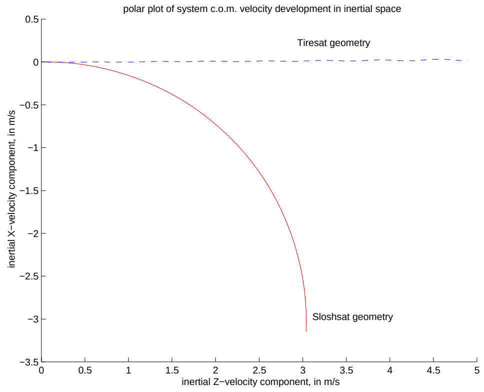

Figure 6 C.o.m. velocities for different spacecraft geometry's, under rotation rate control

The stability polynomial for Tiresat has, in distinction from the Sloshsat case, two conjugate complex roots with small positive real parts. Simulations have been run to learn about the behaviour of the unstable system. The supercritical Tiresat with d=0.05 , sp = 0.00728 , $\varphi_0 = 0.02\ \pi$, has been simulated for rate control torque $T_c = T_{c\ ref} - K\ \theta'$, K = 12, and control delay times of 1/3 and 1" . Repeats with a subcritical Tiresat gave results that are very close to those for the supercritical configuration. The inertial velocity development is illustrated in Figure 6 and is like that of Sloshsat with correct $T_{c\ ref}$. However the amplitudes of state variable excursions increase steadily, shown in Figure 7 for the attitude, which eventually leads to swirling liquid and to failure to maintain a straight course. Unless a new (dynamically) stable state is reached, which actually has been found when gain was reduced from 12 to 4. The run with gain K = 4 was with sp = 0.001, lowered from the earlier Sloshsat value because the Tiresat geometry may reduce the centering action of the capillary force. Eventually it was found that this reduction had no significant effect. The periodic variations in state variables showed much larger amplitudes than for gain 12 and are about constant after 350". The amplitude of φ becomes 94°, i.e. no full swirls are predicted.

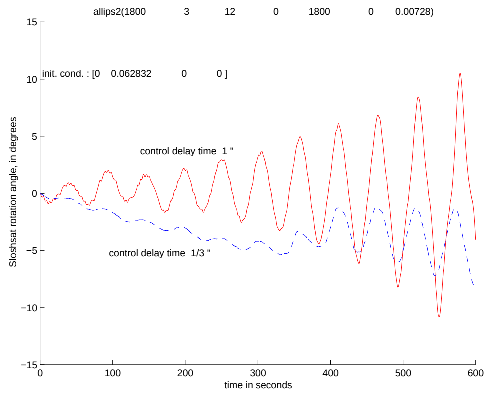

Figure 7 Attitude of Tiresat with thruster offset d = 0.05 m, under rotation rate control

The new equilibrium is characterized by a resonance between tank attitude θ and liquid location φ , such that the magnitude N of the tank-liquid normal interaction force varies between zero (at extremes of θ+φ values) and thrust magnitude F (at extremes of θ′+φ′) . At N = F , tank and liquid masses are aligned with the line of thrust, i.e. φ = 0, and centrifugal force provides the balance. The resonance frequency, about 1/75 Hz, is reflected also in the control torque, illustrated in Figure 8.

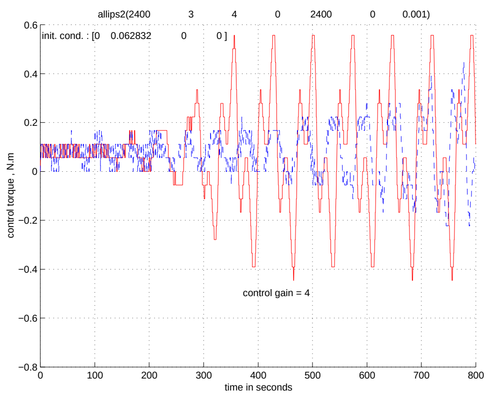

Figure 8 Control torque profiles of subcritical Tiresat for gain magnitudes 4 and 12, and sp = 0.001

The low gain results in the higher torque values; the maximum in the figure corresponds to the maximum torque the RCS can generate. When this maximum torque value is reduced to 0.3 N.m, the equilibrium is not achieved. Instead, a rotating equilibrium state is established and linear momentum does not build up.

The gain 12 data are shown also in Figure 8 and illustrate the growth of control torque corresponding with the increasing attitude amplitude in Figure 7. A final equilibrium similar to the gain 4 case is to be expected.

If the Sloshsat geometry is specified with $0 > a > -L$ (i.e. $\varphi_{ref} = \pi$) , it becomes unstable like Tiresat, but with a much lower positive value for the real part of (two of) the roots of the stability polynomial and no clear instability developed in practical simulation run times.

The conclusion from this exercise is that unstable systems can interact with a control law to establish a new equilibrium. The new equilibrium may still allow the generation of hazardous linear momentum.

7. Control for safety

The specific safety issues are:
- how to inhibit inadvertent linear momentum generation when attitude control remains active and thrust persists, for some time or until fuel is exhausted, and
- how to assure a final state that allows to recover the vehicle without too much trouble. This latter issue will not be addressed now, save to remark that the viscous dissipation of (kinetic) energy will eventually result in an equilibrium rotation of the system about its axis of maximum moment of inertia , aligned with the angular momentum vector at the time of torque termination.

In connection with the Sloshsat recontact hazard, some alleviating strategies have been assessed. The hardest problem occurs for spin-stabilized vehicles, as these do not require attitude control, and some strategies will not work. Strategies based on nonautonomous provisions, e.g. derived from GPS service, have not been considered. The hazard by Sloshsat has been countered via the simple expedient of sending the system in hibernation after a number of tandem thruster firings have been counted by hardware timer circuits. A like measure could possibly be devised to act on a system rotation rate larger than a set value. It could be the closing provision for all schemes that only seek to inhibit linear momentum accumulation. Candidate strategies are:

1. use control that rotates the spacecraft

When thrusting to achieve a specified increase of linear momentum, use a control to bring to zero the system rotation rate, rather than an attitude control. The necessary ability to go to the required initial attitude can be expected to be provided in all spacecraft of interest.

With a nonzero $T_{c\ ref}$ a rotation rate will be generated together with the linear velocity increase. The ultimate value of this rate can be selected by choice of gain K. A further option is to add ($T_{c\ ref}$ / K_p) to the rate value in the control law. Then the system will be torqued unless gain K equals K_p and this condition could be made conditional on proper performance. Eventually, the imposed rate can be zeroed after termination of thrust. This strategy does not work for spin-stabilized spacecraft.

2. introduce a system characteristic that puts constraints on control such that errors need to be special in order to produce catastrophe

Using hardware provisions a time cycle can be implemented such that parallel thrusters will fire in tandem only at even cycles, but only one will fire at odd cycles even when both are commanded. Put differently, one (same) thruster in each tandem is inhibited at odd cycles. For a suitably chosen cycle time the constraint should not sensibly reduce system performance. However, failures that result in firing commands without observing this cycle are reduced in hazard. The strategy may work also for spin-stabilization but the final state of any failed system will be rather unpredictable.

Somewhat similar, but a software provision and therefore not yet considered acceptable, would be:

3. automatically modify a command when it does not fit within the preplanned sequence of operations

Commands not generated in accordance with the procedural constraint will then be without the key property that makes them effective. Considered is not a software implementation of the previous strategy 2, but a more simple measure is meant. An example may clarify:
For each control cycle the Sloshsat onboard computer generates a force and a torque that need to be realized. The next algorithm, one that translates this request in thruster commands, verifies that the required magnitudes are within the capability of the RCS. If found too large, the whole request is scaled down, i.e. the ratio between required force and torque magnitudes is maintained. Implemented should be a time cycle and a factor that takes a high value during even cycles, a low value at odd. The factor multiplies the requested torque before the translation algorithm is entered.
The strategy is based on the observation that commands for linear momentum generation include only requests for small torque, quantified by a gain factor in the closed-loop attitude (rate) control law. Commands for angular momentum have no thrust request. The momentum generation manoeuvre must be planned at the low value of the multiplication factor. If mistakenly commanded during the high value period, thrust will be much reduced and fuel is wasted on very stiff, or overstable control of attitude.

8. Concluding remarks

The computed results shown in the paper are speculative because the used models have not been validated. Nevertheless, the results are plausible and therefore give guidance as to what to expect in actual spacecraft behaviour. Validation of models can be achieved by processing of the data from manoeuvres of STARDUST or like spacecraft.

Liquid swirl has been found not easy to stop; natural decay via viscosity may be the only dependable method. Consequently, operations scenarios for spacecraft with a partially filled tank should anticipate swirl handling.

Safety strategies require specifications if to be proven acceptable ("the devil is in details") for some use, and are not comprehensive. Sloshsat appears to offer scope for testing some 'solutions'.

Whether a control design approach particular for spacecraft with liquid is advantageous, is not certain at present. More general strategies, applicable as well to vehicles without sloshing fuel, may be found to deal successfully with the safety issue for all spacecraft.

Acknowledgement

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